FINAL REPORT

Understanding the Role of Typhoons, Fire, and Climate on the Vegetation Dynamics of Tropical Dry Forests: Looking to the Past to Develop Future Management Solutions

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14. ABSTRACT

Gaining an understanding of the range of environmental variability and the impacts on dry forest form and function is critical in order to effectively manage and restore these systems. The focus of this study was to examine the viability of developing coupled reconstructions of vegetation change, wildfires, and extreme typhoons over the last few millennia for the island of Guam. More than forty coarse layers were deposited in the deepest portion of Cocos Lagoon over the last 2700 years. Cores from the Geus River delta provide a high-resolution record dating back more than 600 years of both marine and river sourced flooding. Pollen is well preserved in both the lagoon and delta sediments, though more abundant in the later. Fossil charcoal is also well preserved in the delta sediments providing an excellent proxy record of wildfires. Our results demonstrate that the sediments deposited in Cocos Lagoon provide a unique opportunity to reconstruct detailed paleoecological and paleoclimatological data that can help improve our understanding of the complex interplay between climate, typhoon activity, fire, human land use, and dry tropical forest ecosystems.

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List of Acronyms

DoD – Department of Defense

ENSO – El Niño/Southern Oscillation

XRF - X-ray fluorescence

Keywords

Dry Tropical Forests, Management, Restoration, Climate, Typhoons

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Understanding the Role of Typhoons, Fire, and Climate on the Vegetation Dynamics of Tropical Dry Forests: Looking to the Past to Develop Future Management Solutions

Abstract

Little is known about environmental controls on the composition, structure, and function of degraded and endangered tropical dry forest ecosystems. Gaining an understanding of the range of environmental variability and the impacts on dry forest form and function is critical in order to effectively manage and restore these systems. An ideal approach to examine how ecosystems develop and respond to changing environmental conditions is to reconstruct the history of vegetation and environmental change using paleoecological proxies. The focus of this study was to examine the viability of developing coupled reconstructions of vegetation change, wildfires, and extreme typhoons over the last few millennia for the island of Guam. We collected a series of sediment cores from Cocos Lagoon on the south coast of Guam guided by geophysical surveys. More than forty coarse layers were deposited in the deepest portion of Cocos Lagoon over the last 2700 years. Cores from the Geus River delta provide a high-resolution record dating back more than 600 years of both marine and river sourced flooding. Pollen is well preserved in both the lagoon and delta sediments, though more abundant in the later. Fossil charcoal is also well preserved in the delta sediments providing an excellent proxy record of wildfires. Our results demonstrate that the sediments deposited in Cocos Lagoon over the past several millennia provide a unique opportunity to reconstruct detailed paleoecological and paleoclimatological data that can help improve our understanding of the complex interplay between climate, typhoon activity, fire, human land use, and dry tropical forest ecosystems.

Objective

Dry forests are thought to be the most degraded and endangered ecosystems in the tropical Pacific (see Murphy and Lugo, 1986). Yet little is known about the environmental controls on the composition, structure, and function of tropical dry forest vegetation. Gaining an understanding of the range of environmental variability and the impacts on dry forest form and function is critical in order to effectively manage and restore these systems. This is particularly important in the light current projections of changes in global and regional climate (IPCC, 2007; Emanuel et al., 2008). This work provides an opportunity to demonstrate that a detailed reconstruction of vegetation change, wildfires, and extreme typhoons over the last few millennia for the island of Guam is feasible. The results from this suite of reconstructions will provide essential data that will inform dry forest restoration and management activities throughout the tropical Pacific. Given changing disturbance, climatic, and land use regimes it is essential to develop this kind of base line data in order to set appropriate and attainable management and restoration goals. Tropical dry forests in the North Pacific, from Hawaii to the Marianas, are particularly susceptible to catastrophic typhoon strikes. As there are numerous DoD installations that contain dry tropical forest that are susceptible to similar changes in climate, land use practices, and disturbance regimes, this work will provide valuable insights into how to best manage and restore these ecosystems at many DoD installations.

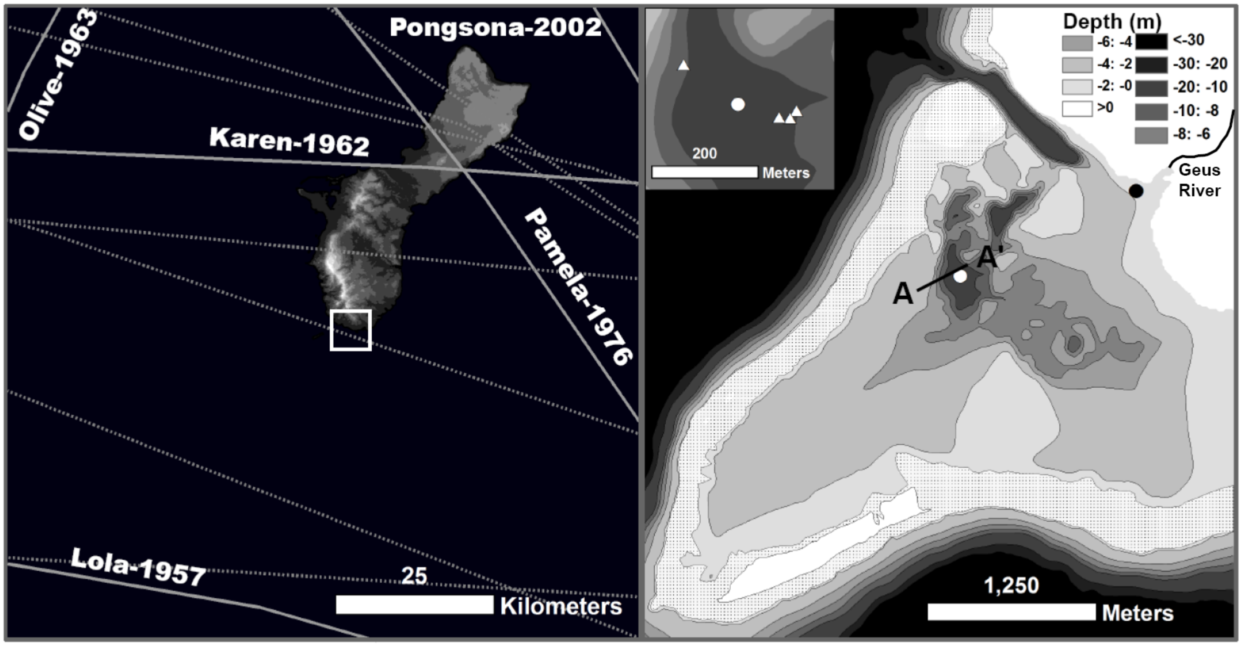

Figure 1 – Map of Guam with typhoon tracks since 1945 (left). Dotted tracks are category 1 and 2 storms. Solid tracks are category 3, 4, and 5 storms. Box indicates location of Cocos Lagoon. Bathymetric map of Cocos Lagoon (right). Location of VC9 noted with white circle. Location of VC3 noted with black circle. Line A to A' is the location of the profile in Figure 2. Inset is a close up of the lagoon hollows and the location of core VC9 (white circle) and other cores (triangles).

Much of the recent effort to understand the effects of climate change on forest ecosystems have focused on the capacity of plants to tolerate temperature and moisture changes, but the effects of disturbances caused by climate change have largely been ignored (Dale et al., 2001). However, modeling efforts reveal that climate change can significantly alter disturbance regimes (Baker et al., 1991; Baker, 1995; Turner et al., 1998; He and Mladenoff, 1999; He et al., 1999). Given predictions of increasing typhoon frequency and intensity in the western North Pacific (Emanuel et al., 2008), dry tropical forests may experience dramatic changes in the frequency, intensity, size, and timing of disturbances. Thus we need to better understand how disturbance regimes may change and how dry tropical forests will respond to them. Using a paleoecological approach linked with evidence of past changes in climate and disturbance regime (see Hotchkiss and Juvik, 1999; Hotchkiss, 2004; Vitousek et al. 2004) is the best way to develop this understanding and these records will provide detailed information to appropriately guide restoration and mitigation efforts. The current work demonstrates that detailed high-resolution reconstructions of past environmental and ecological changes within the dry tropical forest ecosystems of Guam are possible. Follow on work developing these records will help address several fundamental questions: 1) How do dry forest ecosystems respond to frequent typhoon disturbance? 2) How is the fire regime of this ecosystem impacted by frequent intense typhoon strikes? 3) How does this ecosystem respond to a lack of typhoon disturbance? 4) What is the impact of changes in precipitation regime on the vegetation and fire regime of dry tropical forests? 5) How have these ecosystems been altered by legacy land uses? and 6) What are appropriate management and restoration targets given changing environmental conditions?

Cocos Lagoon on the southern coast of Guam (Fig. 1) provides an ideal setting to record past changes in vegetation composition, as well as fire and intense typhoon frequency. The 725 hectare lagoon was extensively studied by Emery (1962). The triangular shaped lagoon is formed on two sides by barrier reefs on a third side by the island of Guam. A large portion of the lagoon is relatively shallow (<6 m) and is dominated by sandy sediment. A deeper portion of the lagoon, termed by Emery "the lagoon hollow" is composed of several interconnected basins some of which are over 12 m deep (Figs 1 and 2). Relatively fine grained sediments are normally deposited in these basins, however during extreme typhoons surge and waves likely transport coarser grained material from the surrounding reefs and lagoon into the lagoon hollow preserving a record of the typhoons passage. The Geus River empties into the northeast part of the lagoon and drains a watershed composed of volcanic derived rocks and soils.

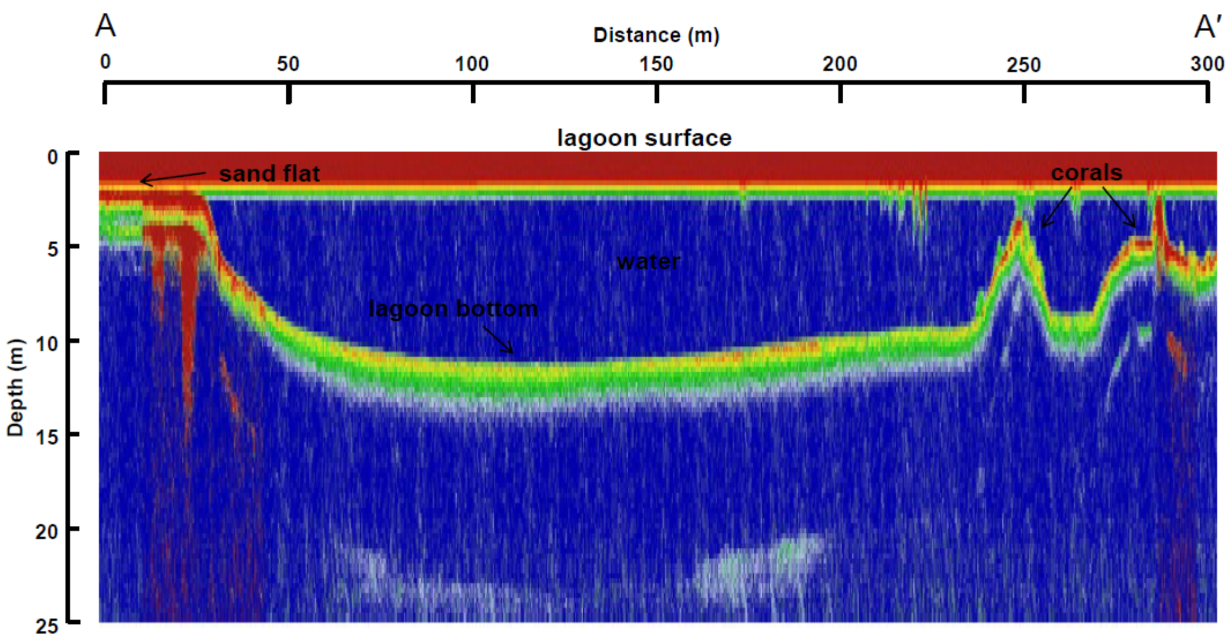

Figure 2 – 10 kHz Stratabox™ profile from A-A' on Figure 1 showing a cross section of the lagoon hollows.

During normal "quiescent" conditions pollen and charcoal from the island of Guam are transported by wind and water to Cocos lagoon and deposited with the fine grained sediment in the lagoon hollow. Thus, in addition to providing a record of past extreme typhoons, these sediments provide a long-term record of vegetation and wildfires. Furthermore the terrestrial material transported from southern Guam via the Geus River and deposited in Cocos Lagoon provide a proxy for the amount of runoff. Thus, the deep basins within Cocos lagoon provide an ideal setting to explore the relationship between typhoons, fire, and climate and the dry tropical forest communities. The principal objective of this proof of concept work is to confirm that such a record exists in order to facilitate a larger project aimed at fully developing these reconstructions.

Background

Tropical Cyclone Induced Forest Disturbance

Intense tropical cyclones can play a significant role in controlling forest ecosystem form and function (Foster, 1988; Conner, 1995; Gresham et al., 1991; Pascarella and Horvitz, 1998; Myers and van Lear, 1998; Boose et al., 1994; 2001). Nevertheless, little is known about the specific long term impacts of intense tropical cyclones in the ecology for the majority of forest types (Myers and van Lear, 1998). Intense tropical cyclones (category 3-5; sustained winds >50 m s^{-1}) often result in catastrophic disturbance to forests, where most or all of the canopy is removed (Boose et al., 2001; Spur, 1956; Hook et al., 1991; Hooper and McAdie, 1995). Many historical examples of widespread mortality to forest trees across large areas are available (Hedlund, 1969; Lugo et al., 1983; Whigham et al., 1991; Boucher et al., 1990; Hook et al., 1991; Myers et al., 1993; Loope et al., 1994). The landscape patterns resulting from these disturbances are strongly affected by interactions between the tropical cyclone, the abiotic environment (e.g., topography and soil type), and the composition and structure of the vegetation when the disturbance occurred (Foster et al., 1998; Lugo, 2008). These interactions yield distinctive temporal and spatial ecological patterns and require that we better understand the physical characteristics of typhoon disturbance processes. Intense typhoon disturbances create legacies of physical and biological structure that impact ecosystem processes for hundreds of years or more (Foster et al., 1998, Lugo, 2008).

The overall consequence of intense tropical cyclones on coastal forests depends not only on the intensity (wind speed) and spatial scale of the storm, but on the duration, rainfall amounts, number of embedded tornadoes, soil conditions, forest structure, topographic heterogeneity, storm surge magnitude, and extent of salt spray (Boyce, 1954; Weaver, 1989; Gardner et al., 1991; Hooper and McAdie, 1995; Lugo, 2008). Salt introduced via storm surge can cause a significant amount of plant mortality in lower lying areas near the sea (Gardner et al., 1991). Salt spray during intense tropical cyclone landfalls can be transported over 100 km inland and can also stress or kill plants (Boyce, 1954). Kerr (2000) documented significant defoliation on Guam as a result of salt spray associated with Typhoon Gay in 1992; however this island-wide phenomenon was not associated with stand-level mortality. Mortality rates of trees do increase after some intense cyclone events, and patterns of mortality are based on the topographic position, stature, and life history characteristics of each tree (Lugo, 2008). The spatial scale of cyclones can also influence mortality rates and affect the amount of canopy disturbance, which in turn controls the source (seed dispersal vs. sprouting) and rate of regeneration (Horvitz et al., 1998). The scale of impact is dependent on the proximity of the track, intensity, and radius of maximum winds of the typhoon. The eye radius of northwest Pacific super typhoons (minimum pressure of ≤ 920 mb) is typically between 10 and 20 km (Weatherford and Gray, 1988). Given the relatively small size and elongate shape of the island of Guam, the vast majority of super typhoons making landfall in southern Guam would result in significant ecosystem disturbance across the entire southern portion of the island (the area that comprises the watershed for Cocos Lagoon).

Tropical forests respond to catastrophic cyclone events on time scales ranging from minutes to several hundred years (Lugo, 2008). Cyclones initiate a large pulse in the accumulation of

debris, and often trigger landslides with large debris flows (Lugo, 2008). Immediate effects from high winds include massive defoliation and wind-thrown trees, with an accompanied alteration of light, temperature, and humidity. The immediate loss of canopy has negative impacts on vertebrate communities, particularly bats, such as the *Pteropus mariannus* (mariana fruit bat), which may not return to cyclone-damaged forests for years (Esselstyn et al., 2006; Lugo, 2008). The canopy and leaf area index can recover quickly through sprouting, rapid seedling establishment, or refoliation, but recovery is generally patchy. In fact, an idealized life history characteristic for trees adapted to large infrequent disturbances such as cyclones includes sprouting, root grafting, small size, short life span, rapid change in leaf adaptations to sun or shade, and rapid seedling establishment (Lugo, 2008). In time, cyclone-damaged forests will show dramatic changes in species composition and structure, diversity, basal area, stem density, and nutrient cycling (Lugo, 2008). However, the trajectory of response to cyclone events is controlled by whether fire or drought occurred after the event and the nature of land use before the event (Zimmerman et al, 1995; Lugo, 2008).

Recently an increasing number of researchers have linked human-induced climate change, which is thought to have increased sea surface temperatures (Levitus et al., 2000; Levitus et al., 2001), and the frequency and intensity of tropical cyclones (Webster et al., 2005; Emanuel, 2005; Emanuel et al., 2008). Simulated hurricane climatologies based on a series of global climate models suggests that the western North Pacific may experience a dramatic increase in tropical cyclone activity in the coming century. Such an increase in the frequency of intense tropical cyclone landfalls would profoundly impact the form and function of coastal ecosystems. In fact, given their potential for widespread catastrophic disturbance, increasing numbers of typhoons may pose a greater threat to coastal terrestrial ecosystems than most other phenomena associated with climate warming including sea-level rise. Understanding how ecosystems may respond to more frequent intense tropical cyclone disturbance is difficult to predict. Even predicting the response to a single cyclone is challenging, given the complexity of cyclone interactions with landscape heterogeneity, soils, and type of ecosystem. Additionally, significant literature on cyclone effects on ecosystems has only emerged since the 1990's, few of which consider the effect of multiple cyclones (Lugo, 2008). An ideal way to examine how ecosystems will respond to future disturbance is to look to paleoecological records that document past responses to disturbance regimes similar to what may occur during the coming decades (e.g., Brown et al., 2005). Reconstructions of intense tropical cyclone landfalls in the western North Atlantic reveal significant variability in the frequency of these events through time (Liu and Fearn, 2000; Donnelly et al., 2004; Donnelly, 2005; Scileppi and Donnelly, 2007). For example, a 5000-year reconstruction of intense hurricane activity from a lagoon on the island of Vieques in the Caribbean indicates several extremely active intervals followed by periods of quiescence (Donnelly and Woodruff, 2007). These fluctuations in intense tropical cyclone activity have been tied to changes in the West African Monsoon and El Niño/Southern Oscillation (ENSO).

In comparison to the western North Atlantic, centennial-to millennial scale typhoon reconstructions from the western North Pacific are far more limited. Historical government documents of typhoon landfalls from the Guangdong Providence in Southern China extend back 1000 years, although complete records for typhoon strikes to the region are likely only reliable back to 1600 AD (Lee and Hsu, 1989; Qiao and Tang, 1993; Chan and Shi, 2000; Liu et al., 2001). Arakawa et al. (1961) have also put together an assemblage of historical documents describing typhoon occurrences in Japan between 701 AD and 1865 AD. Recent efforts are also

underway to compile additional Japanese records for typhoon landfalls (e.g., Grossman and Zaiki, 2007). Woodruff et al. (2009) reconstructed extreme marine flooding events from two coastal lakes in southern Japan over the last 6400 years. The data indicate an inverse correlation with Atlantic records that may link the activity in both basins to ENSO-like variability.

In the western North Pacific, the overall number of tropical cyclones is less affected by ENSO (Wang and Chan, 2002); however, the mean genesis location for typhoons generally shifts to the southeast during El Niño years (Chan, 1985; Lander, 1994). This shift results in longer lasting typhoons (Wang and Chan, 2002), which generally become more intense (Camargo and Sobel, 2005; Chan, 2007). Thus, tropical cyclones impacting Guam during El Niño like conditions are likely to be more intense than those that occur in La Niña like conditions.

Wildfires

Typically fires result from lightning strikes or humans and can burn for months during long periods of drought (Foster et al., 1998). Weather conditions, vegetation, and the distribution of firebreaks control fire size, intensity, and return frequencies, and produce fire regimes that vary on a broad scale. In turn, these contrasting regimes can produce distinctive long-term patterns in forest structure, composition, and the distribution of fire-generated legacies. In the dry tropical forests of the Pacific fire can create a mosaic of forest and grassland and very frequent fires may convert forested landscapes to savannas or grasslands (Vieira and Scariot, 2006). In many tropical regions, dry forest conversion occurred after the invasion of non-native grasses which in turn increased fire frequency to a level that was historically uncommon (Hughes et al., 1991). Wildfires following catastrophic typhoons also may play an important role in restructuring forest ecosystems (Myers and van Lear, 1998). The danger of fire increases following intense tropical cyclones, due to large fuel accumulations (Spurr, 1956; Webb, 1958; Craighead and Gilbert, 1962; Furley and Newey, 1979; Gardner et al., 1991; Hook et al., 1991; Whigham et al., 1991; Loope et al., 1994), and the more open canopy leading to increased drying (Gill et al., 1990; Loope et al., 1994). Fire can dramatically slow the process of recovery, by making recovery more dependent on vertebrate seed dispersal than on sprouting (Hjerpe et al., 2001). Webb (1958) noted that composition and structure of rainforests in Queensland, Australia are affected by the interaction of tropical cyclones and fire, and that changes in the frequency and intensity of tropical cyclones and fire may produce different community types.

Fire is an important ecosystem component on the southern portion of Guam, which is covered with a mosaic of ravine and scrub forests interspersed with grassland dominated by the native grass *Miscanthus floridulus* (Mueller-Dombois and Fosberg, 1998). Grasses have been present, at very low abundances, on southwestern Guam for the past ca. 10,000 years (Athens and Ward, 2004). Fires began in the record only ca. 3,500 yrs ago, soon after human arrival, during a time when grass levels were nearly non-existent (Athens and Ward, 2004). The occurrence of prehistoric fire in these tropical Pacific forests is most often associated with human settlement and agroforestry projects (e.g., Athens and Ward, 2004). However, it is likely that increases in fire frequency may have been the result of changing climate and typhoon frequency as has been suggested in the northern Gulf of Mexico (Liu et al., 2008). A very high temporal resolution sediment record can provide definitive evidence for whether fire regimes changed with human agroforesty or with variation in typhoon activity.

Climate Change

Climate variation likely plays a key role in determining the form and function of dry tropical forest ecosystems. In particular the amount and seasonality of precipitation likely play a key role in controlling the structure and composition of these systems. Climate models suggest that in addition to future changes in temperature, precipitation patterns will likely change over the coming decades. For example model results predict an increase in precipitation over much of the tropical North Pacific over the next 100 years (IPCC, 2007). In addition warming sea surface temperatures may fuel more intense typhoons (Webster et al., 2005; Emanuel, 2005; Emanuel et al., 2008).

Paleoclimatic records document significant shifts in tropical climate phenomena over the past several thousand years. For example, Haug et al. (2001) document shifts in the position of the intertropical convergence zone (ITCZ) over Venezuela. Similarly variations in ENSO have been documented. El Niño events became more frequent over the last 10,000 years with millennial scale intervals of alternating high and low ENSO activity superimposed on this long term trend (Moy et al., 2002). Centennial scale swings from humid to drought conditions have been documented in some tropical locations (Hodell et al., 2001). By looking to the past we can determine how dry tropical forests respond to changing climate regimes, human land use regimes, and fire regimes to inform future management and restoration efforts.

Potential Hypotheses

The instrumental record of typhoons in the Pacific is extremely limited (extending back to the beginning of the satellite era at some locations). However, the data available suggest that Guam is more likely to experience extreme typhoons during an El Niño event (Saunders et al., 2000; Elsner and Liu, 2003; Camargo and Sobel, 2005). Primarily this is likely a result of an eastward shift in the area of tropical cyclone genesis during El Niño events. In addition, drought conditions are common in Guam during El Niño events (Neelin et al., 2003).

Paleoclimatic reconstructions and climate modeling indicate that ENSO variability was suppressed during the mid-Holocene and increased during the last few thousand years (Clement et al., 2000; Moy et al., 2002). Thus, if the relationship between ENSO and typhoons observed for the recent instrumental record holds for the last several millennia we would expect that Guam (and other areas of the North Pacific) experienced an increase in extreme typhoon disturbance over the past few thousand years. Further, these more frequent El Niño conditions likely resulted in generally drier conditions in the southern Marianas during the last few thousand years.

Athens and Ward (2004) document an increase in disturbance indicators (including charcoal) in western Guam over the last several thousand years. Notably the onset of the presence of charcoal at this site occurs around 3,500 years ago when the frequency of El Niño events increases (Moy et al., 2002). Below we highlight some hypotheses that we will be able to test with the further development of high-resolution reconstructions of typhoons and forest disturbance is preserved in Cocos Lagoon.

- Extreme typhoon strikes increased markedly on Guam over the last few thousand years.

- This increase in forest disturbance contributed to the conversion of dry tropical forest to open savanna on the south coast of Guam.
- This transition from dry tropical forest to savanna was facilitated by an increase in wildfires following catastrophic typhoon blow downs likely exacerbated by El Niño forced drought conditions.
- Vegetation response to typhoon events varied according to the overall climate/typhoon, fire, and human land-use regimes.
- These past perspectives, coupled with various scenarios for future typhoon activity, will allow for the development of restoration strategies appropriate to the current land use regime on Guam.

In order to test these hypotheses it will be necessary to distinguish between human-induced changes in vegetation and typhoon disturbance. A major goal of this project is to produce an independent record of typhoon landfalls that will provide the basis for our analysis of forest disturbance. Human disturbance leaves distinctive evidence in the pollen record. For example, in the absence of changing typhoon activity, the initial period of coastal settlement with some upland slash-and-burn agriculture would likely be recorded as an increase in charcoal influx, an increase in Poaceae, *Gleichenia*, *Palhinhaea cernua*, Cyperaceae, and possibly an increase in spore production by tree ferns with removal of canopy trees. In addition, pollen evidence of cultivated non-native plants will likely be present (e.g., *Colocasia esculenta* (taro)). Coincident with later increases in land clearance, we would expect a further increase in the above mentioned taxa and a decline of trees and shrubs, with steadily increasing charcoal accumulation rates. Eventually this progression would lead to a lack of forest and the pollen recorded will be dominated by grass, sedge, fewer understory ferns, trees, and shrubs (similar to the present day ecosystem of southern Guam). Charcoal influx rates would likely remain high or moderate.

Conversely, typhoon-induced changes to the forest will immediately follow an event layer, independent evidence of typhoon landfall, and would likely be reflected by a rapid decline of tree and shrub pollen accumulation rates without preceding increase in charcoal influx rates. If charcoal influx does increase, it will occur following evidence for forest disturbance. Increases in light-loving taxa such as Poaceae, *Gleichenia*, *Palhinhaea cernua* may or may not follow this abrupt typhoon related disturbance, depending on the degree of resprouting and the recovery rate. Of course changes in typhoon regimes may prompt changes in strategies by the people living on the island. As a result these records may not be completely independent. Fortunately the typhoon event record will be in the same sediments as the pollen and charcoal data so we can look at direct temporal correlation and lead-lag analyses between those records, using ordination scores or multivariate estimates of rates of change in the pollen assemblages. These can then be compared with the records of storm events and charcoal accumulation rate.

The Cocos Lagoon record will enable us to examine the influence of typhoon impacts in the absence of human disturbance if the record extends back far enough in time. The presence of charcoal in sediments has led some to infer human settlement of Guam occurred as early as 4,300 years ago (Athens and Ward, 2004). However, as we discuss above, there are other potential mechanisms that could result in fires on Guam. The earliest concrete evidence of human agriculture on Guam is taro pollen that dates to 1,100 years ago (Athens and Ward, 2004). If our hypotheses are viable and the increases in charcoal and the conversion of dry tropical forest to savanna were driven by increases in extreme typhoon disturbance and drought,

it would cast substantial doubt on the interpretation that human land clearance occurred as early as 4,300 years ago. This is one way in which the proposed work could shed some light on the impact of legacy land use.

Given that a high-resolution record of typhoons, fire, and forest composition does appear to exist in Cocos Lagoon we will be able to tease apart the various factors that contributed to the transformation of the dry tropical forest ecosystem on Guam. Additionally, with deep enough cores, we have the temporal resolution to take a detailed look at response to specific typhoon events, and categorize response based on human land use regime, frequency of typhoon events, and frequency of fire. With these records we can address how vegetation response to typhoons varies with land management and we can highlight which taxa are most sensitive or resilient to typhoons and fires. Developing this understanding will provide critical baseline information for setting attainable restoration and management goals. If we understand how this ecosystem responded to past environmental changes (whether it be humans, changing typhoon disturbance, or a combination of the two) it will provide critical baseline information that will help us predict what future changes might occur. Future climate warming may bring more frequent intense El Niño events (see Timmerman, 1999) that could lead to more frequent typhoon landfalls and drought in Guam. Increased disturbance from typhoons and El Niños may provide new opportunities for invasion by non-native species, but their persistence in a landscape is context- and species-dependent (Lugo, 2008). Future work will provide valuable insight into what changes we might expect in the remaining dry tropical forest in Guam and many other areas of the Pacific Ocean.

Materials and Methods

Sample Collection

We used portable 10 kHz Stratabox™ and 4-24 kHz EdgeTech profilers to map Cocos Lagoon and target core sites. Nine cores were taken with a portable underwater vibracore system hand driven with extension rods. Core recovery was generally between 3 and 5 meters. Cores were transported back to Woods Hole Oceanographic Institution (WHOI) and refrigerated at 4 degrees Celsius.

Sample Analysis

Cores were split longitudinally and an archived half was scanned on the WHOI XRF core scanner. The scanner provides rapid, non-destructive, ultra-high-resolution core analyses of X-ray fluorescence (XRF) bulk geochemistry, digital X-radiography, and digital photography. The μ-XRF capillary technology employed by the scanner provides rapid measurements of all chemical elements from Al (atomic number 13) to U (atomic number 92), at a spatial resolution as low as 200 μm. We sampled the working half of selected cores contiguously at 1 cm resolution. Particle size distributions (~1 μm to 2000 μm) were measured using a Beckman-Coulter LS13320 laser diffraction device on cores VC3 (Geus River Delta; Fig. 1) and VC9 (lagoon hollow; Fig. 1). The coarse fraction greater than 2000 μm for core VC9 was determined by sieving 7-10 cm^3 contiguous samples and weighing this fraction relative to the dry weight of the initial sample. Loss-on-ignition analysis was conducted on contiguous 1 cm^3 samples in VC3 to estimate the percentage organic matter composition of the sediment (Dean, 1974). Macrofossils and bulk

organic carbon samples were radiocarbon dated at the National Ocean Sciences Accelerator Mass Spectrometer Laboratory at WHOI. Radiocarbon results were calibrated for secular changes in atmospheric radiocarbon concentrations using the IntCal2009 dataset (Reimer et al., 2009). For recent age control Cs-137 activity of selected subsamples from VC3 were measured at WHOI using a high-resolution gamma detector (e.g., Donnelly and Bertness, 2001).

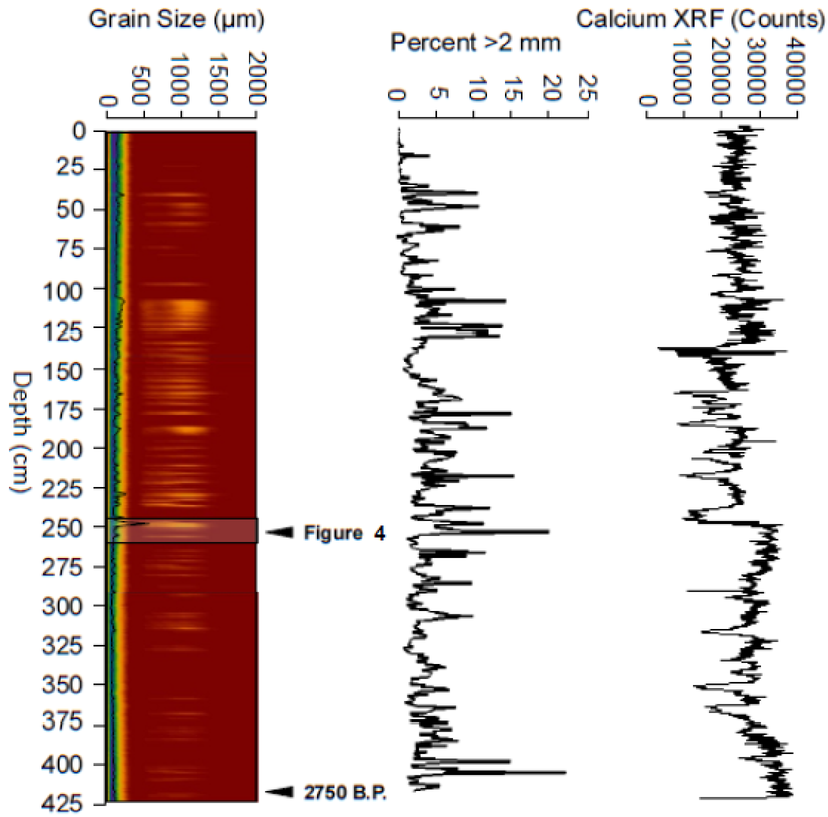

Figure 3 – Grain size contour plot of particles in VC9 between 20-2000 µm (left) ranging from 0 (maroon) to 6 (blue) percent by volume. Line superimposed over contour plot is the d90 grain size where 90% of the grains fall below that value. Location of radiocarbon dated sample is noted. Location of photograph shown in Figure 4 is shown. Center plot is the percent greater than 2 mm particles measured with sieving. Calcium counts from the XRF scanner (right).

Pollen Reference Material

We collected pollen and spores from live plants in the Geus River watershed on Guam and from existing specimens housed at the University of Guam Herbarium to create taxonomic references specific to Guam. We collected 77 samples, including 63 species (24% of which are thought to be non-native) representing 33 families of angiosperms and pteridophytes common to the ravine forests and savanna complex in southern Guam. Samples were subjected to 10% KOH

and acetolysis and then mounted in silicon oil on microscopic slides to create an archival library of pollen reference material. Select types were photographed at 400x magnification.

Pollen Analysis

We prepared one surface sample from a lagoon core (VC9) and eight samples from a delta core (VC3) for pollen analysis. Each sample contained 10 cm^3 of sediment sampled over 2 cm of core depth. We took the eight samples in VC3 at approximately 60 cm intervals. To calculate pollen concentration (grains/cm^3), one tablet with a known amount of exotic *Lycopodium* spores was added to each sample before processing. Samples were processed using standard pollen preparation techniques including acetolysis (Faegri and Iversen, 1989). Additionally, all eight samples from VC3 were treated with hot 10% nitric acid to remove pyrite. At high temperatures, nitric acid can remove pyrite, but it may also destroy pollen exines, and thus be counterproductive for pollen analysis (Faegri & Iverson 1989). To test the effect of nitric acid on the pollen assemblage, one of the eight samples from VC3 was also prepared without the nitric acid treatment.

Figure 4 – Photograph of a coarse grained layer in VC9.

All sample residues were mounted in silicon oil and counted at 400x magnification. Taxonomic references included the new Guam-based reference collection, Selling (1946, 1947), and a Polynesian-based reference collection maintained in the Quaternary Ecology lab at the University of Wisconsin-Madison. Pollen percentage calculations were based on a sum of all pollen and spore types, which averaged 104 grains in a sample. Pollen and spore data are presented in diagrams as percentages. Taxa were grouped into herbs, trees and shrubs, mangroves, ferns, and unknown/indeterminate types. Within each group, the taxonomic resolution of pollen identification ranges from family to genus to species. For example, grasses (Poaceae) can only be identified to the family level, which precludes answering questions about native versus non-native grasses. However, many human cultigens (*Cocous nucifera*, *Areca catechu*, *Colocasia esculenta*, etc.), indigenous tree and shrub species (*Aglaia mariannensis*, *Elaeocarpus joga*, *Triumfetta procumbens*, etc.) and non-native tree and shrub species (*Vitex parviflora*, *Myrica rubra*, etc.) can be identified to the species level. We

Table 1 - Radiocarbon Results

Core	Material	Lab #	d13C	Age	Error	cal age (yrs BP)	2 σ max	2 σ min	probability	Depth in core (m)
VC9	bulk organics	OS-74401	-12.67	2610	30	*2750	2776	2624	1	4.2
VC3	leaf fragment	OS-73850	-26.61	595	30	610	652	539	1	4.8
VC3	wood fragment	OS-73849	-26.19	360	30	450	499	316	1	3.7
VC3	plant fragment	OS-73848	-28.32	375	25	465	503	319	1	2.1
VC3	plant fragment	OS-73847	-25.01	215	25	160	304	147	0.883	1.01

* assumes carbon is of terrestrial origin (i.e. no marine reservoir correction is applied);
if carbon is of marine origin and a standard correction is applied the age would be approximately 2300 years BP

used the software TILIAGRAPH to plot the pollen diagram and perform stratigraphically constrained cluster analysis (CONISS) of the pollen assemblages (Grimm, 1987).

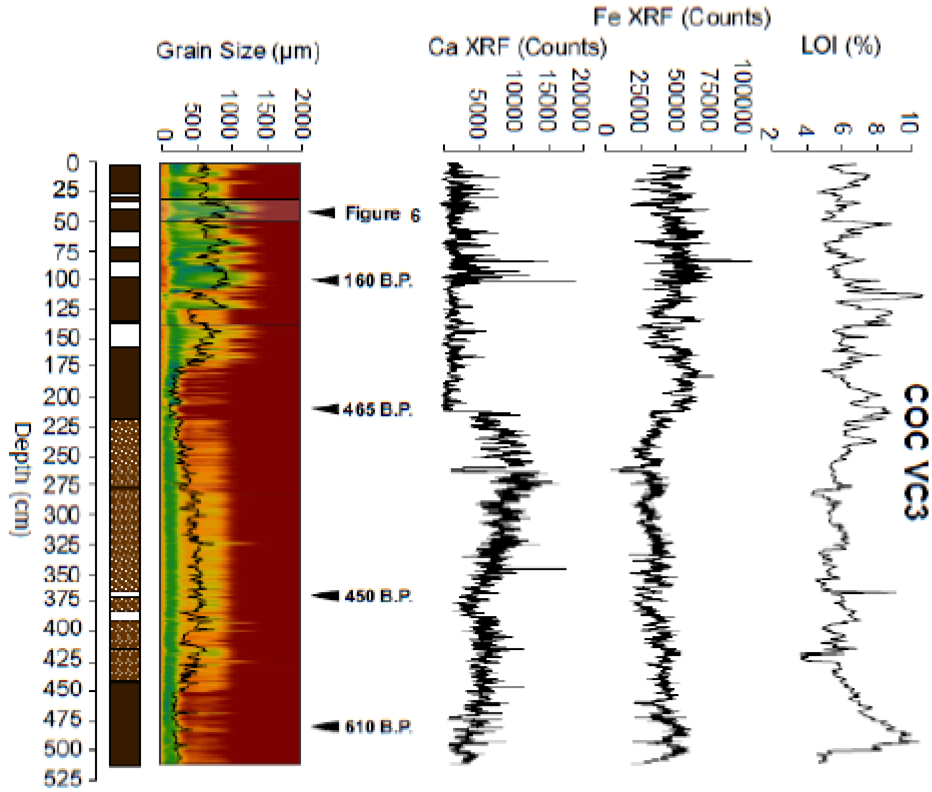

Figure 5 – Stratigraphic column of VC3 with grain size contour plot of particles in VC3 between 20-2000 µm (left) ranging from 0 (maroon) to 6 percent (green) percent by volume. Brown is silt. White is coarse grained event layers. Brown stippled is silt with shell fragments. Line superimposed over contour plot is the d90 grain size where 90% of the grains fall below that value. Locations of radiocarbon dated samples are noted. Location of photograph shown in Figure 6 is shown. Calcium (Ca) and iron (Fe) counts from the XRF scanner (center). Loss on ignition (LOI) values are shown on the right.

Charcoal Analysis

In order to test the viability of a wildfire reconstruction we quantified macroscopic charcoal particle concentration (pieces/cm^3) in several samples from a lagoon core (VC9) and a delta core (VC3). We analyzed 11 samples from VC9, each of which contained 10 cm^3 of sediment sampled over 1–4 cm of depth. We analyzed nine samples from VC3, each of which contained 3–5 cm^3 of sediment sampled over 2 cm of depth. All samples were treated with 10% HCl, washed through a 125 µm sieve, and treated with H_2O_2 to bleach non-carbonized organic material. Each of the 11 samples from VC9 was also washed through a 63 µm sieve to capture the 63–125 µm size class. All 31 samples were counted on a dissecting microscope at 20x (Parshall et al., 2003).

Results and Discussion

Sediment Record

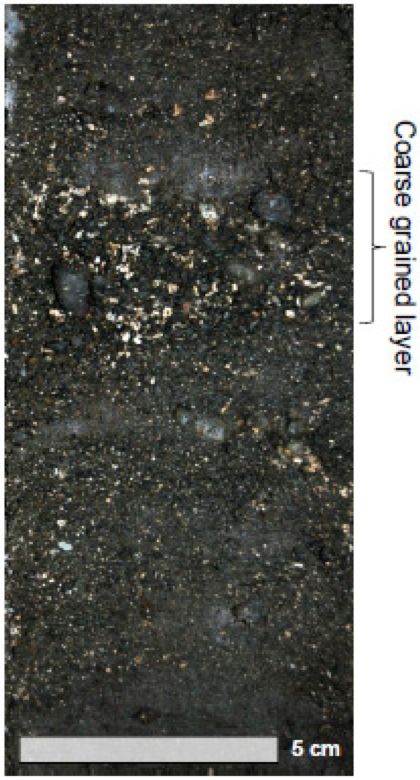

Figure 6 – Photograph of a coarse grained layer in VC3.

Geophysical surveys of Cocos Lagoon on the southern margin of the island of Guam (Fig. 1) were used to map the bottom of the lagoon. These surveys revealed that the lagoon hollows, first described by Emery (1962), are relatively flat bottomed depressions with a maximum depth of roughly 12 meters. The lagoon hollows are bounded by sand flats and coral reefs (Fig. 2). Core VC9 was located in the center of the lagoon hollow and recovery was about 4.25 m. The sediments in the lagoon hollow predominantly consist of silt and fine sand with layers of coarser shell hash and coral fragments.

Grain size measurements using the Beckman-Coulter laser diffraction instrument reveal a remarkably stable primary mode in particle size around 125 µm with a range from roughly 25 to 250 µm (Fig. 3). Superimposed on this baseline distribution of particles are a series of coarse sediment layers that contain particles that range from approximately 500 to 1500 µm. Sieving at 2000 µm revealed that many of the coarse layers also contain a significant amount of particles in excess of 2000 µm. Figure 4 depicts one of the coarsest deposits recovered in the core at approximately 250 cm. These coarse sediments consisting primarily of coral and shell fragments were transported to the lagoon hollow from the adjacent flats and reefs during high

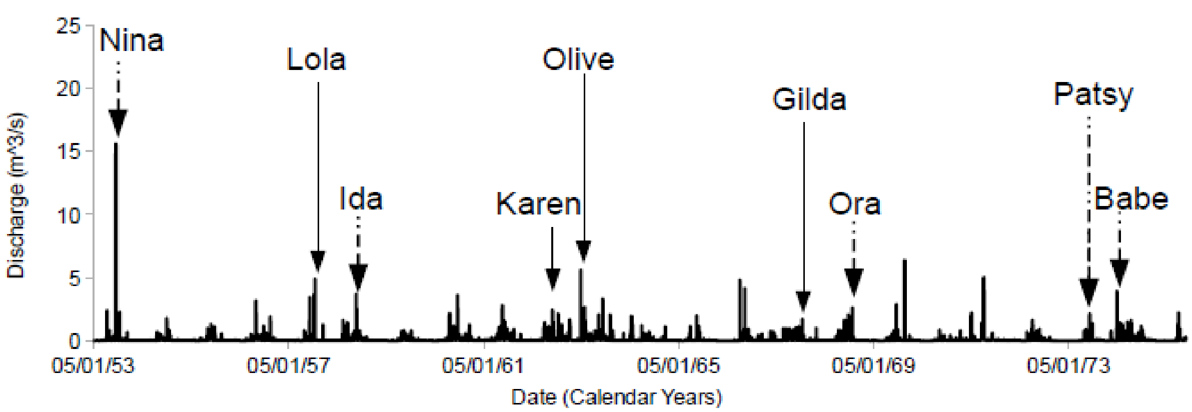

Figure 7 – Stream gauge data from the Geus River from 1953 to 1975 (USGS, 2010). Typhoons impacting the Guam over this interval are noted.

energy events, most likely catastrophic typhoon landfalls.

A calibrated radiocarbon date from near the base of the core yielded and age of approximately 2750 years before present (where "present" is 1950 AD by convention; Table 1). Based on this age the average accumulation rate for the entire core is roughly 1.5 mm/year. Significant variability in the frequency of the coarsest layers (e.g., those that exceed more than 5% greater than 2 mm) is evident (Fig. 3) with clustering of event layers at 30-65, 100-130, 160-310, and 350-410 cm. Many of the peaks in coarse fraction also correspond to lower amounts of Ca detected in the core on the XRF scan (Fig. 3). However, grain size effects on the XRF beam may account for these apparent drops in relative Ca concentration. The most recent peak coarse fraction occurs at about 17 cm and is comprised of roughly 4% particles over 2 mm. Extrapolation of the sedimentation rate derived from our one radiocarbon date to the top of the core suggests that the layer at 17 cm may have been deposited in the late 19th century. Based on this very preliminary age model it appears that none of the typhoon strikes in the instrumental record (see Fig. 1 for summary) left a coarse layer in the middle of the lagoon hollows.

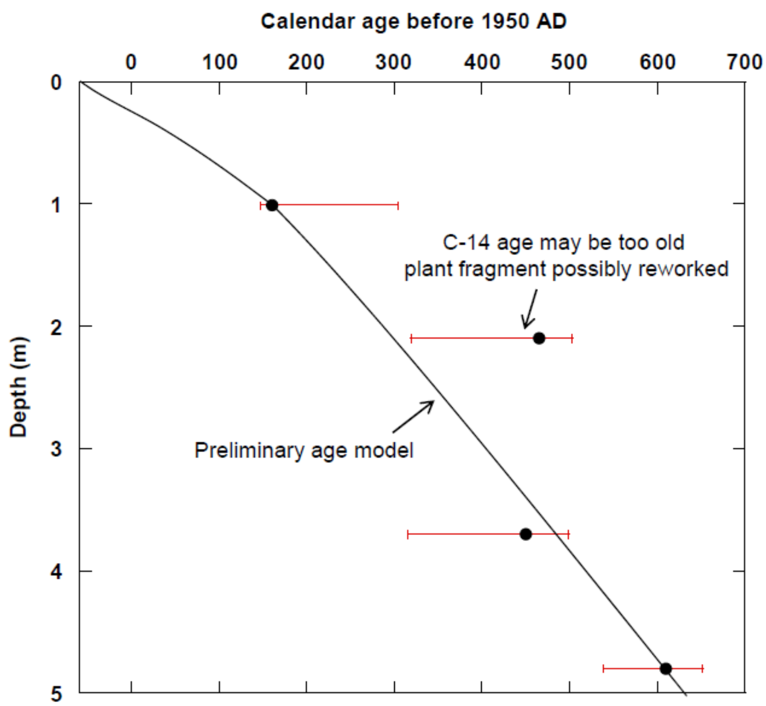

Figure 8 – Calibrated radiocarbon ages for VC3 at 2σ versus depth. Black line is the preliminary age model.

The instrumental record indicates that twelve typhoons have passed within 60 km of Cocos Lagoon since 1945 (JTWC, 2010; Fig. 1). Of these only five were major tropical cyclones (≥ to category 3 on the Saffir-Simpson scale; sustained winds over 96 knots). The two most intense tropical cyclones to strike Guam 65 years were Super Typhoons Karen (1962) and Pamela (1976). While both of these storms made landfall in Guam at category 5 intensity, the trajectory of each of these storms (making landfall in northern Guam) spared Cocos lagoon from experiencing catastrophic surge and waves as peak winds came from the onshore direction. Super typhoon Lola in 1957 passed roughly 50 km to the south of Cocos lagoon causing only moderate flooding in southern Guam. No catastrophic super typhoons have made landfall in southern Guam in the last several decades. The lack of any recent (20th century) typhoons in the sedimentary records of the lagoon hollows may indicate that the threshold for typhoon-induced deposition at the location of VC9 is quite high with only the most catastrophic typhoons passing over southern Guam with extreme onshore winds leave a sediment record. As a result of only being sensitive to more extreme typhoons, the sediment record of the lagoon hollows is ideal for examining the impacts on terrestrial ecosystems as the record does not contain event layers

associated with numerous weaker typhoon strikes that did not have an appreciable ecological impact.

Figure 9 - Images of pollen and spores from the mangrove trees *Rhizophora apiculata* (a), *Barringtonia asiatica* (b), the fern *Angiopteris eretica* (c), the small tree *Maytenus thompsonii* (d), the shrub *Hibiscus tiliaceous* (e), and the fern *Ceratopteris gaudichaudii* (f) from the Guam-based reference collection. All images were taken at 400x magnification.

VC3 was collected from the Geus River delta at the northern margin of Cocos Lagoon in about 1.5 m of water (Fig. 1). Approximately 5.15 m of sediment was recovered. Several coarse grained deposits are present in this core as well (Fig. 5), though they are a combination of shell hash and large clasts (≥1 cm) composed of volcanic rocks (see Fig. 6). The combination of marine derived sediment (shell hash) and upland volcanic suggests that these event layers were likely laid down during typhoon strikes that also resulted in significant rainfall and flooding in the Geus river watershed. In fact a stream gauge operating on the Geus River from 1953 to 1975 (USGS, 2010) reveals that many of the extreme discharge events over that interval were the result of typhoon-induced precipitation (Fig. 7).

The organic content of the delta sediment ranges from 4 to 10 % (Fig. 5). Grain size measurements from the Beckman Coulter laser diffraction device indicates peaks in grain sizes that correspond to the coarse grained deposits in the upper 1.75 m of the core. From 2.20 to 4.35 m the sediment is slightly less organic and contains more carbonate rich sediments. Ca levels are generally higher in this interval and Fe levels are relatively low (Fig. 5). While grain size measurements appear to indicate coarser sediments in this interval only two coarse grained layers are evident visually at 3.70 and 3.85 m. The greater variance in grain size in this interval is related to an increase in the concentration of shell hash in this unit. The increase in shell hash in the sediment matrix, more abundant calcium, lower organic content, and lower relative amounts of Fe point to more marine influenced sedimentation with less river discharge during this interval.

Four samples were radiocarbon dated from VC3 (Figs. 5 and 8; Table 1). The calibrated dates suggest that the base of the core is roughly 600 years old. The remaining ages suggest an average accumulation rate of 6 to 8 mm/year (Fig. 8). The plant fragment from 2.1 m in VC3 is older than would be expected given the other three ages and was likely reworked, thus it may not reflect the age of deposition. The rapid accumulation of sediments at this location results in an extremely high-resolution record. On average each centimeter of deposition is roughly equivalent to 1.5 years. Gamma decay counting results indicate significant Cesium-137 to a depth of at least 1.1 cm (see appendix). Given Cesium-137 should be present in sediments younger than the early 1950s these results are inconsistent with the radiocarbon results and suggest that Cesium-137 is mobile in the delta sediment.

Pollen Reference Material

Of the 77 samples of reference material processed, 84% produced enough grains to be used as a taxonomic reference. Now, 54 species native to Guam have been added to the reference collection maintained in the Quaternary Ecology lab at the University of Wisconsin-Madison. This new Guam-based reference collection was the primary taxonomic reference used to identify the majority of types represented in the pollen diagram. Select types are shown in Figure 9.

Pollen and Charcoal Analysis

Adding nitric acid to the pollen processing protocol for delta core sediments increased pollen concentration (Fig. 10) and species richness (20 vs. 14 types), and decreased the percentage of indeterminate grains (6% vs. 15%). Pollen concentration for most of the nitric-treated VC3

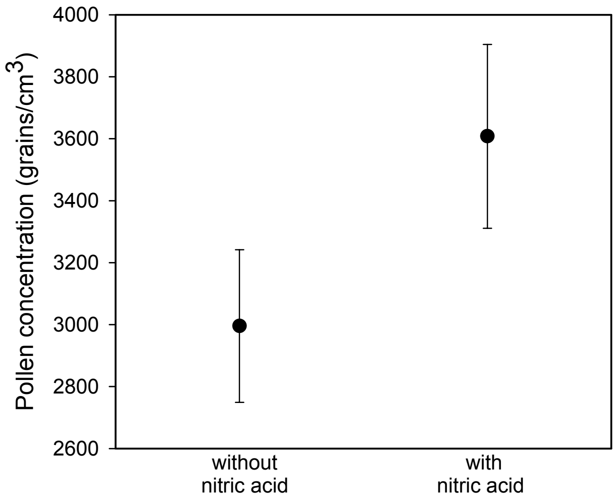

Figure 10 - Effect of adding nitric acid to the pollen processing protocol on pollen concentration for one sample from VC3.

record averaged 3,700 grains/cm^3, but was an order of magnitude higher at the base (Fig. 11). Pollen concentration in the lagoon core (VC9) was much lower (290 grains/cm^3).

Pollen assemblages from the delta core (VC3) clustered as two major vegetation zones, which split at ~240 cm in depth (~ 400 conventional radiocarbon years ago). Grasses (Poaceae) dominated the earlier assemblages below 240 cm (zone 1), whereas the ravine forest tree *Pandanus* (Pandanaceae) dominated above 240 cm (zone 2). Macroscopic charcoal particle concentrations for both size classes of samples in the lagoon core (VC9) were very close to zero (>125 µm

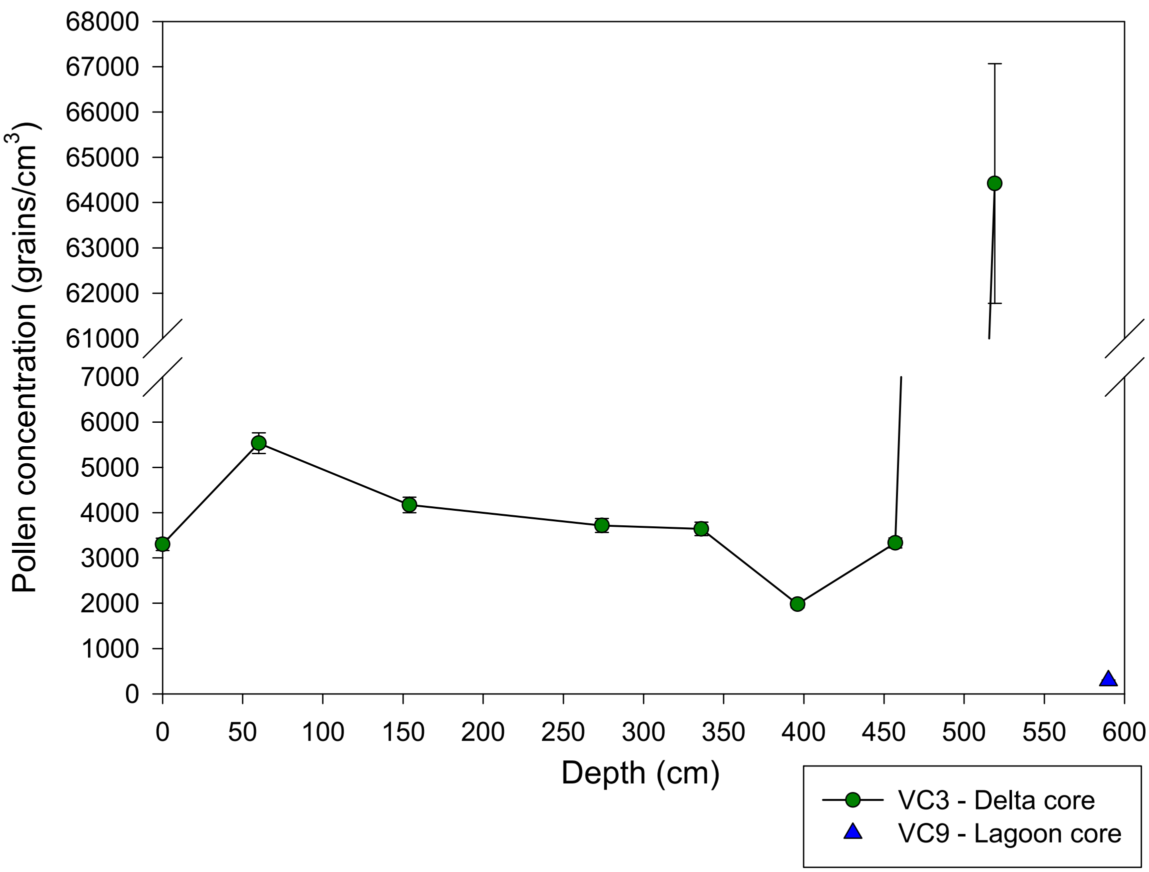

Figure 11 - Pollen concentration for all samples in stratigraphic order from a delta core, VC3. Note: pollen concentration from a lagoon core VC9, was much lower at 290 grains/cm^3.

range: 0–0.5 pieces/cm^3, 63–125 µm range: 0–0.2 pieces/cm^3). The concentration of charcoal particles >125 µm in the delta core VC3 averaged 27.2 pieces/cm^3 (range 11.2–58.8, Fig. 12 right-most graph). Average charcoal concentration was higher in the grass-dominated zone 1 (30.3 pieces/cm^3) than in zone 2 (23.4 pieces/cm^3), but the difference was not significant (t-test, *P*=0.52)

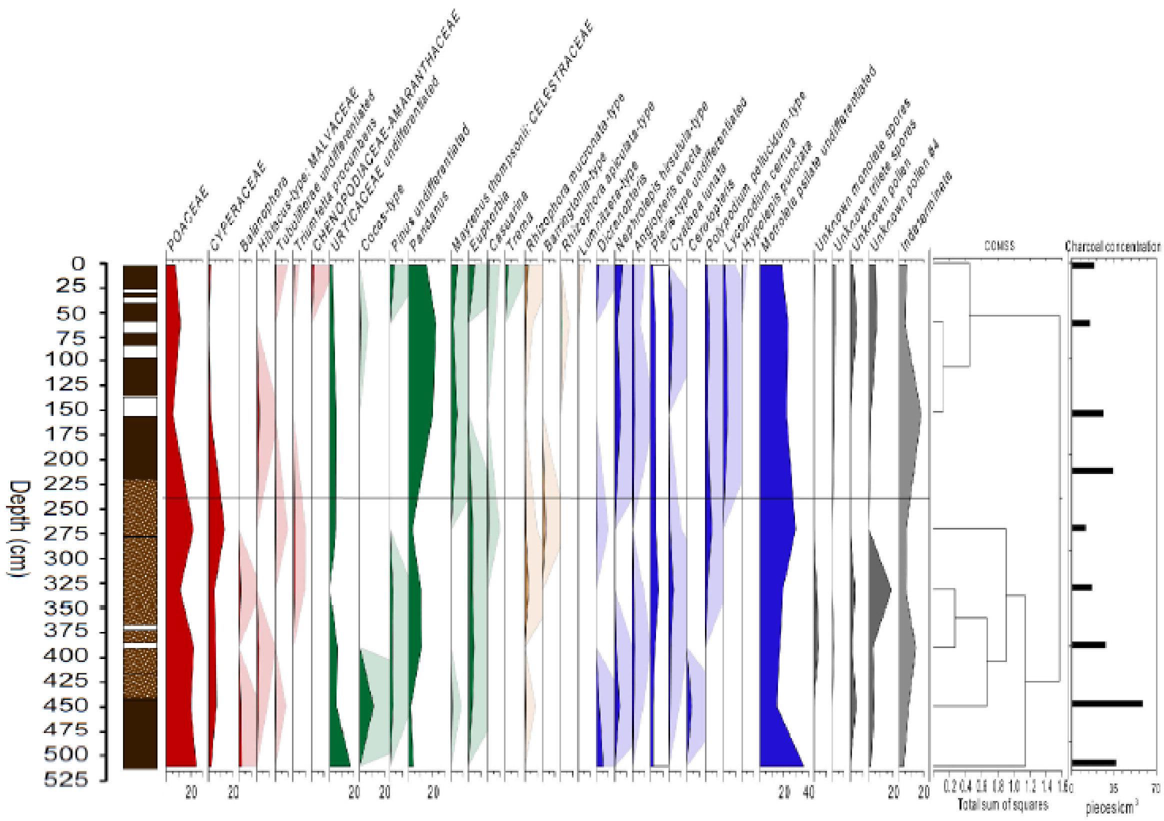

Figure 12 - Pollen diagram showing the percentage of each pollen and spore type (x-axis) according to depth (y-axis) from a delta core, VC3. Types are grouped by life form – herbs (red) trees and shrubs (green), mangroves (brown), ferns (blue), and unknown/indeterminate (gray). Lighter shades of each color show a 10x exaggeration, to highlight the pattern of rare types. The CONISS cluster dendrogram is shown at right, and divides the pollen diagram into two main zones (zone 1 below 240 cm and zone 2 above 240 cm). The right-most graph shows the stratigraphic record of charcoal concentration from VC3.

We have developed a taxonomic reference system and a sediment processing protocol that can produce a high-resolution record of vegetation on Guam. Pollen concentration in the lagoon sediment is low, but well within the range of published marine palynological studies (10–5,000 grains/cm^3, Hooghiemstra et al., 2006). Pollen concentration in delta sediment is at the upper end of the marine range, and shows excursions an order of magnitude higher, into the range of lake sediment. This rich concentration of pollen in delta sediments, coupled with very high temporal resolution and the preservation of a charcoal record, offers an unprecedented opportunity to reconstruct high-resolution vegetation and fire dynamics.

The preliminary pollen record shows that vegetation changed around 400 years ago, in an abrupt switch from a grass-dominated assemblage towards more *Pandanas*. *Pandanus* is a common component of ravine forests, and therefore its abrupt increase suggests that ravine forest may have increased in the area as the savanna complex declined. This shift in vegetation may correspond with a relative decrease in catastrophic typhoon landfall in the last few hundred years. Our data also show an isolated peak in *Cocos*-type (coconut) several hundred years ago, concurrent with a large peak in macroscopic charcoal, suggesting an agroforest initiated by fire. This work verifies that a high-resolution pollen and charcoal record is preserved in the Cocos Lagoon sediments and that these records can be used to reconstruct fire, vegetation composition, vegetation change, and shifts in human land-use over time.

Conclusions and Implications for Future Research/Implementation

The combined preliminary records of catastrophic typhoon strikes, terrestrial runoff, vegetation change, and wildfires generated from this proof of concept study clearly demonstrate that valuable detailed paleoclimatological and paleoecological reconstructions are possible from the Cocos Lagoon sediments. Follow on work will be proposed to develop these reconstructions. This work will include extracting longer cores from Cocos Lagoon in order to extend our reconstructions as far back in time as feasible, in order to capture a record of different land use, climate and typhoon regimes. This is particularly critical in the Geus River delta where high sedimentation rates have resulted in a relatively short amount of time represented in VC3. Extending the record so that it reaches beyond the arrival of humans to Guam (ca.4500 years ago) will provide a means of understanding how different land use regimes structure recovery after typhoons and for determining the true cause of dry forest conversion to grassland – humans or increased typhoon intensity. These data will help shape restoration goals, by addressing whether this conversion was anthropogenically driven, and will help managers reach these goals, by providing detailed information on how land use affects recovery after typhoons. Employing an advective settling model we can use the grain-size distribution within individual typhoon deposits to calculate the relative intensity of past typhoon events (e.g., Woodruff et al., 2008). The very high temporal resolution will also allow us to examine the details of plant recovery after typhoons of different strength, and determine which taxa are most sensitive to typhoon events, and whether rate-of-change differs with intensity level. Additionally, these records will provide evidence for the consequence of invasive tree species identifiable in the pollen record, such as *Vitex parviflora*, on tropical dry forests.

Once completed these coupled reconstructions will reveal how changes in catastrophic typhoon frequency, precipitation regime, invasive species and fire affect the vegetation dynamics of tropical dry forest ecosystems and will provide an important benchmark for predicting how this ecosystem will respond to changes in future intense typhoon activity and climate as well as shape restoration goals. Expectations of anthropogenic alteration of the global climate system and increased numbers of intense tropical cyclones particularly underscore the need to understand the impact of frequent catastrophic disturbance on this valuable and threatened ecosystem. The results can be integrated into a variety of existing ecological models that examine ecosystem disturbance and climate change (e.g., Boose et al., 2001; Baker et al., 1991; He and Mladenoff, 1999; Loehle and LeBlanc, 1996; Pascarella and Horvitz, 1998; Peterson,

2002) and will improve our ability to predict and manage future changes to these important ecosystems. Our findings may also have important implications for how adjacent ecosystems may be impacted. For example changes to the dry forest ecosystems may lead to changes in nutrient and sediment flux to coastal and nearshore ecosystems. Further, we can make generalizations about the variation in vegetation response to typhoons under different land use regimes that are focused on plant functional type (i.e., sprouter, vertebrate-dispersed, etc.) so as to be directly transferable to management and restoration of other islands in the Pacific.

In summary, when completed, this work can inform current decision making on a variety of levels. We can provide a detailed understanding of how different vegetation types, brought about through different land use regimes, respond to typhoon events of varying intensity and to fire. We can classify vegetation response in terms of plant functional types, thus making these data relevant for islands across the Pacific. Perhaps most importantly, our work can answer fundamental questions regarding what is a "native" dry tropical forest and what is a sustainable dry tropical forest in the future given changing climate and disturbance regimes. In light of climate model projections that point toward significant increases in typhoon activity in the northwest Pacific (Emanuel et al., 2008), our work could cast considerable doubt as to the efficacy of current dry tropical restoration efforts if we were to demonstrate that the conversion to open grassland on Guam resulted from increased typhoon disturbance. In addition, the work will provide lists of taxa that are resilient or sensitive to various disturbance regimes that will enable managers to better assess the viability of future restoration efforts.

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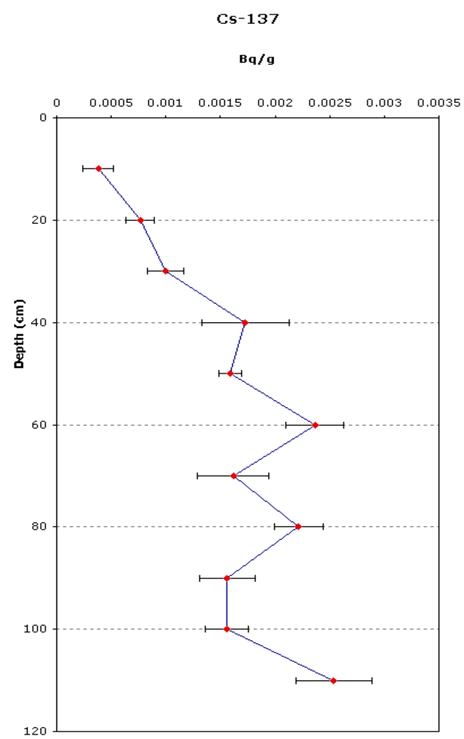
Appendices:

A. Cs-137 data



Cs-137 activity in the upper 110 cm of VC3.